CORRELATION BETWEEN NDE MEASUREMENTS AND PHYSICAL PROPERTIES OF COPPER POWDER METALLURGY COMPONENTS

D. Utrata
Iowa Demonstration Laboratory
Center for Nondestructive Evaluation
Iowa State University
Ames, IA 50011

J. Oswood
Square D Company
3700 Sixth Street, S.W.
P.O. Box 3069
Cedar Rapids, IA 52406-3069

INTRODUCTION

Square D, a world leader in the manufacturing of electrical components and systems, needed to insure it was using only high quality powdered metal (PM) components in one of its' line of circuit breakers products. Low strength powdered metal components had been detected by routine destructive testing practices which subsequently rejected entire lots of product. Although the occurrence of a failure was infrequent, Square D felt that improvements in both the design of the part and method of inspection could be implemented. As a result, the part design was improved which made all of the parts acceptable all of the time with respect to break strength level. Square D was still troubled by the fact that, even though all of the parts were now acceptable, there was still a very low percentage of parts that exhibited lower than average strength.

With an improved part design now in production, Square D embarked on a mission to find a method to inspect 100% of the PM parts that went into circuit breakers. Several inspection methods such as x-ray, ultrasonics, eddy-currents, and resonant inspection were evaluated. The only method that showed real promise was resonant inspection (RI). To further investigate the feasibility of using resonant inspection as a method of detecting low strength parts, Square D teamed up with the Iowa Demonstration Laboratory (IDL) and Magnaflux in an effort to minimize the time required to evaluate this inspection technique. Square D leased RI equipment from Magnaflux for the IDL to use in evaluating this NDE technique. The IDL made an investment in time to receive training on the use of the equipment and performed the collection of data.

Review of Progress in Quantitative Nondestructive Evaluation, Vol. 18
Edited by Thompson and Chimenti, Kluwer Academic/Plenum Publishers, 1999

Resonant inspection seemed to solve the inspection challenge of finding the rare, isolated parts that exhibited poor performance. The aspects of RI inspection peculiar to testing these electrical blades were detailed at a Metal Powder Industries Federation (MPIF) symposium [1]. The task in the current scope of work was to examine more fully the utility of resonant inspection for characterizing and predicting physical properties of PM components. From a manufacturing point of view, it makes sense that those physical properties should also be correlated to mechanical performance. For this study, the resonant inspection data was correlated with sectional and overall density measurements, as well as a measurement of the force required to break the component in question.

At the MPIF symposium the authors saw a presentation given by Dawson [2], wherein he described how density gradients beneath abrupt geometric changes in PM parts were evaluated using ultrasonic velocity measurements. The results presented were intriguing, and the authors decided to include ultrasonic velocity measurements in the battery of tests performed on the test specimens in this study.

PROCEDURE

In developing a test sample matrix, various characteristics of overall part condition and performance were incorporated. This was done in part by selectively modifying the normal manufacturing process for these copper PM components, and also by segregating particular batches out of normal production runs. In this paper, the test groups will be identified as shown in Table 1. Discussion of test results will use these group names.

In this work, resonant inspection testing was performed using a bench top system made by Quasar International and marketed by Magnaflux. Pictures of the inspection equipment and specimen fixturing can be viewed in presentations posted at this web site: http://www.cnde.iastate.edu/idl/pm.html. All test data was recorded on the device leased from Magnaflux, and then analyzed with software installed on an office PC.

It is readily acknowledged that much of the utility of RI testing lies in the clever use of suitable algorithms to analyze test data [1,3]. Specifically, the occurrence of resonant peaks at particular frequencies can be used in a highly efficient manner to characterize a component's state quickly. However, certain constraints existed in this study that required the use of more hastened data collection methods and, perhaps, more cumbersome data interpretation techniques. In these tests, a single band of excitation frequencies ranging from

Table 1. Description of nomenclature used in sample matrix.

Test group name	Characteristics
Old design	Original component, a copper electrical blade having a 90° step at its thin/thick transition region, pressed in single stage compaction process
New design	Same overall blade design, but transition eased to 45° between zones
Machined	Originally a thicker blade, with 90° transition profile created by machining
Undersintered	New design blade that was intentionally undersintered
Sharp	Designation given to new design blades that appeared to have markedly "crisp" edges
Uncoined	New design blade that missed the final coining operation normally used to ensure precise dimensional tolerance.

25 kHz to 125 kHz was applied to the samples. While many different tools exist within the Quasar software to develop and refine algorithms to interpret the response spectra of different samples, only simple observations of peak shifting were made for this work. Acquiring the broadband response of the test samples, and then using the evaluation software to highlight particular narrow bands of frequency range did this. In effect, we took more raw data than (probably) necessary, and distilled it down into simple yet meaningful (we hope) observations of relative behavior.

All of the RI data was obtained on original, full-body specimens. Indeed, this is a major selling point for use of this technique: rapid, inspection of a full component. However, taking ultrasonic velocity measurements on samples in the original condition posed some problems. It was known that the components in question typically failed at a transition zone in the part profile. While ultrasonic C-scans of the parts could be made in their original configuration, a "blurring" of the data occurred immediately adjacent to this region due, presumably, to beam scattering and diffraction. Therefore, two sets of ultrasonic measurements were made on the test samples: point measurements of apparent ultrasonic velocity were made using a Panametrics thickness gage and a dual-element transducer, placed to either side of the transition zone. Also, amplitude-based C-scans were made of these parts in immersion mode after machining the profiles of the parts smooth and planar. This allowed for an observation of the change in apparent velocity as affected by modification to the complex density gradients present in this region, as well as observation of the density distribution over more of the test pieces. A photo/drawing of the test blade, indicating points of sectioning for various density measurements and the planes machined to create smooth surfaces, is shown in Figure 1.

TEST RESULTS

The first test results analyzed were the results of bulk density readings and break force tests performed destructively. The data shown in Figure 2 indicates a trend of increasing force required to break these blades as density increases. However, the outlying point of very low break force demonstrated by a truly bad blade indicates that overall density is not an adequate feature for evaluating such components.

It was reasonable to assume that the properties of the transition region would certainly affect the break strength of these parts. The bulk density of this region was measured, following sectioning according to the sketch in Figure 1. Break force for samples from the various groups in the test matrix was plotted as a function of this density, as shown in Figure 3. While the higher transition zone densities in the "new design" and "sharp" blades correlated to higher break strengths, the lowest break force measured in these samples came from the "uncoined" sample that had a median value of density. Again, this indicates that a single, simple measurement does not seem to predict the component performance very well.

The ultrasonic velocity measurements were undertaken in an effort to determine more detailed information of density distribution and its affect on various parts. An appreciable amount of data was taken on these samples. Good correlation was found to exist between ultrasonic velocity over both thin and thick sections of the various blade groups and measured bulk density, and is shown in Figure 4. This suggests that ultrasonic velocity measurements will have valid implications concerning density, even over the microstructural variations represented by the different groups of samples.

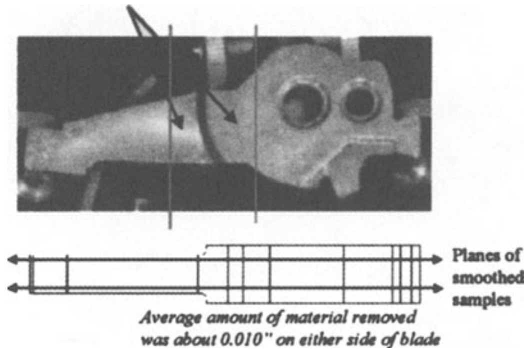

Figure 1. Photo of copper PM electrical blade studied in this report, arrows indicating where UT velocity measurements were made, and lines indicating how part is sectioned into thin, transition and thick sections for density measurements. Lower sketch shows planes of surface material removed to facilitate detailed C-scan inspection.

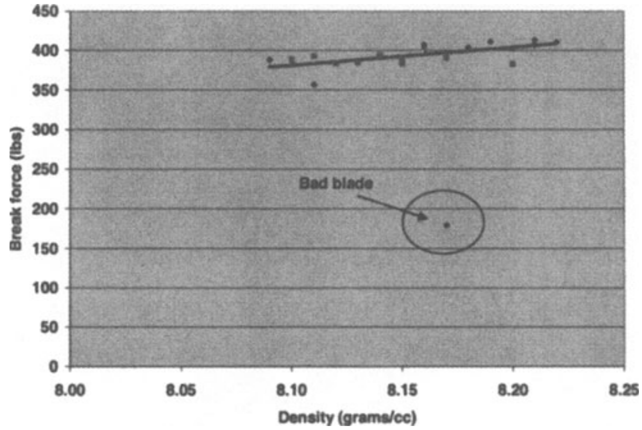

Figure 2. Force required to break a sampling of old design blades, plotted as a function of overall density. Note that an unacceptable blade exhibited a mid-range value of density.

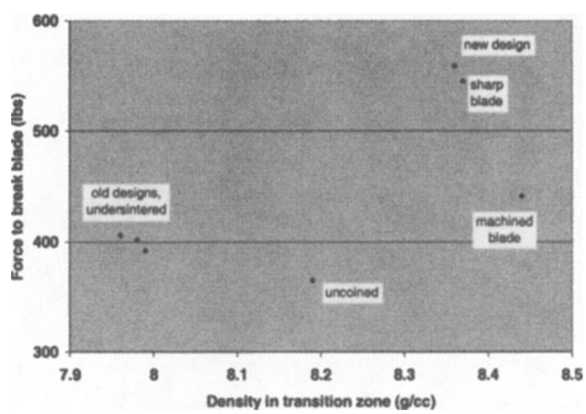

Figure 3. Blade break force as a function of bulk density measured in the transition zone of various blades.

Due to space constraints in this article, not all of the data obtained during the course of this investigation can be presented here. However, various ultrasonic velocity measurements were evaluated and contrasted with the force required to break these blades. This included an analysis of how the velocities changed when the surface layer of material was removed to facilitate the acquisition of C-scans. One interesting observation was that in their original configuration, the thinner end always had a higher velocity (higher density) than the thicker end; with the surface removed, the thicker ends had a higher relative velocity. The thin end velocity always went down subsequent to machining, while the thick end velocity always went up. These observations merit a good analysis of how this reflects the distribution of complex density gradients in the individual pieces, such as indicated in PM textbooks [4]. In the scope of this article however, suffice to say that no clear and simple interpretation of these measurements could be linked to blade breaking force. More data from this investigation will be posted at the web site listed previously.

A composite image created from amplitude-based C-scans of samples of the various blade groups is presented here. Figure 5 shows the scan results, with the transition zone density measurements superimposed next to the corresponding parts. Generally, the three blades that exhibited the lowest transition zone densities also exhibited the strongest amplitudes of backwall-reflected ultrasonic signals, and all occurring just to the thin side of the transition zone. The exception to this "rule" is the normal blade, which also exhibited a pronounced region of high amplitude signal. However, upon close observation of the location of this region, it appears that high-amplitude region in the normal blade occurs at a point somewhat closer to the thicker side of the transition zone. This data strongly suggests the usefulness of making density measurements via ultrasonic velocity readings. However, it also points out the care required to interpret such data for correlation with mechanical part performance.

Resonant inspection results for different blades are shown in Figures 6 and 7. Figure 6 shows the responses of a truly bad blade contrasted with 4 acceptable blades. The data here is expanded to show only a portion of the spectrum of frequencies used to test the blades. Specifically, only the data from about 26 to 29 kHz is shown. The upper two traces were from blades that appeared normal in all respects, exhibiting the response typical of the vast majority of blades. The two lower traces are from blades that were flagged as suspect during RI testing. Recall that no specific algorithms could be used on these samples; as it was not possible to assemble a true training set of samples by which to develop one. This figure shows the inherent power of RI testing to identify unique components, while also stressing that the data does not lend itself readily to an *a priori* interpretation for screening purposes.

Figure 7 shows the RI responses of an undersintered blade, a normal blade and a sharp blade. The frequency shifts of various peaks are indicative of changes in the density of the various blades. This methodology of monitoring the frequency shift of corresponding resonant peaks was applied to samples from the various groups of blades. In some instances, particularly for the uncoined sample, the behavior of peak shifting was not uniform across the full test frequency range. The data for resonant testing of the various samples was then contrasted with overall bulk density values and the force required to break the blades. These results were tabulated and shown in Table 2. With the exception of the uncoined sample, the peak frequency shifts correlated well with both readings of both density and break force.

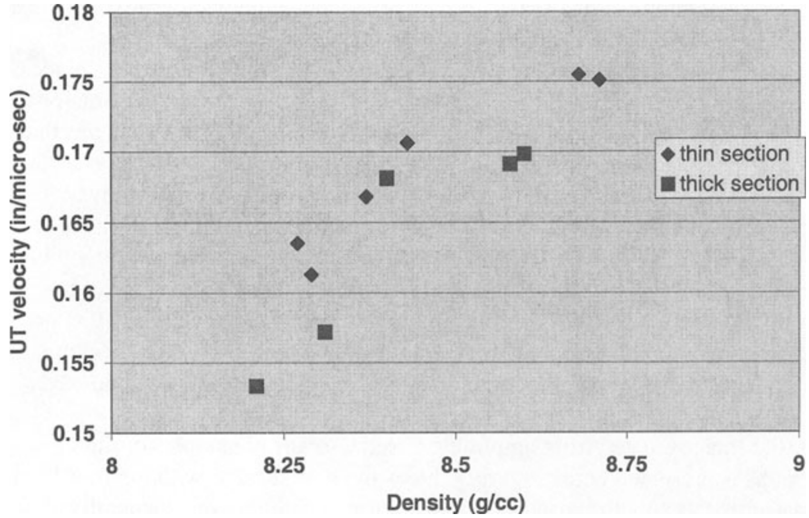

Figure 4. Ultrasonic velocity as a function of bulk density measured n thin and thick sections of copper PM blades. A fairly good correlation exists, even over the range of microstructural variation represented over the various sample groups.

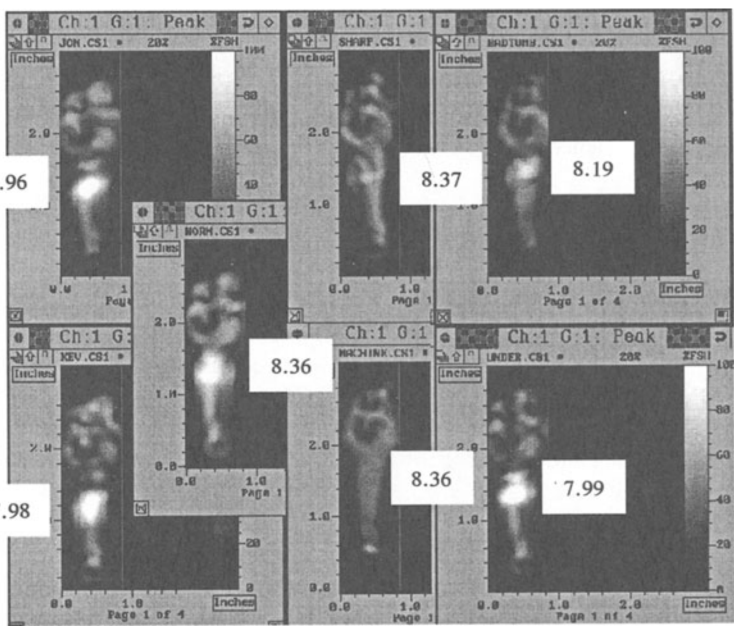

Figure 5. Composite image made from amplitude-based C-scans of reflected backwall ultrasonic signals in various copper PM blades. The three blades in the top row are from the old design, sharp and uncoined groups, reading left to right. The three blades in the bottom row are from the old design, machined and undersintered groups, reading left to right. The lone blade in the center row is from the normal group. Numbers refer to bulk densities, measured in the transition zone of the blades.

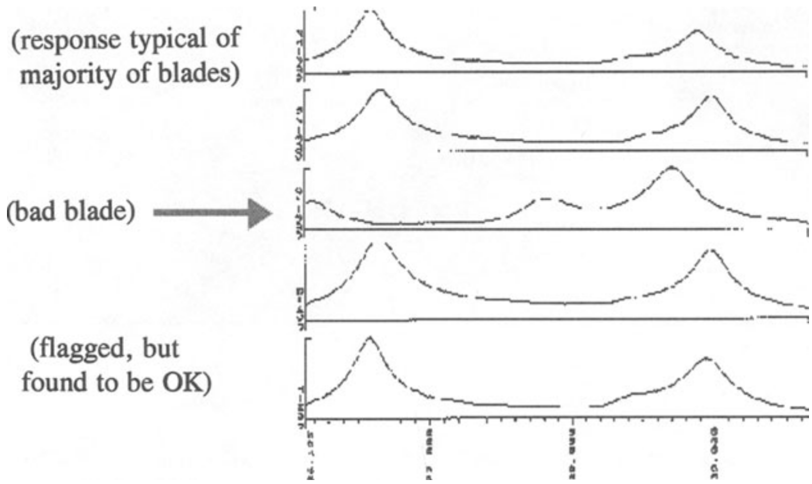

Figure 6. A resonant inspection spectrum for one bad electrical blade is contrasted with the responses of four acceptable components.

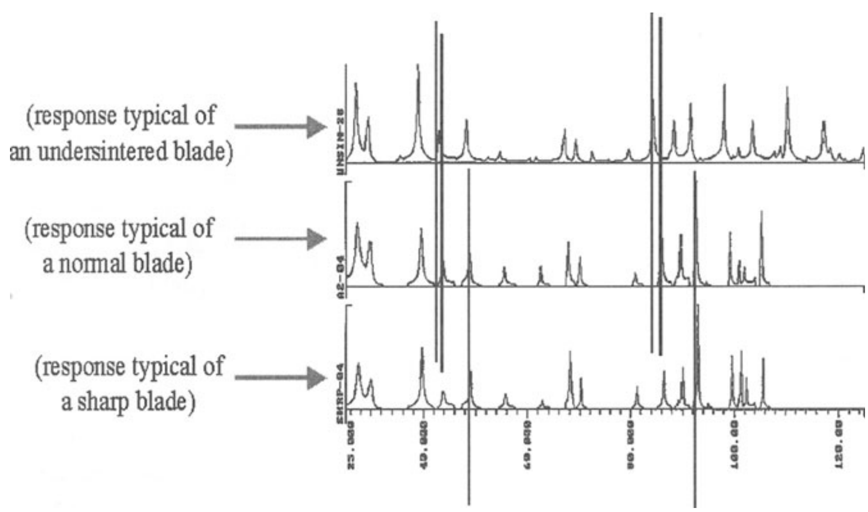

Figure 7. Resonant inspection spectra for undersintered, normal and sharp blades. The analysis of such data was the careful observation of the shifted frequencies of corresponding peaks.

Table 2. RI response for various blades, with overall density values and break force results.

	Difference in RI result	*Overall density (grams/cc)*	*Break force (lbs)*
Undersintered	Peaks ~3 kHz lower	8.27 (3.5% lower)	392
Sharp	Peaks same freq. or slightly higher	8.59 (about same)	545
Uncoined	Peaks ~3 kHz higher, spaced differently @ higher freq.	8.38 (2.3% lower)	365
Machined	Peaks slightly lower	8.4 (1.9% lower)	441
Normal		*8.58*	*559*

DISCUSSION

In this brief paper, the authors strove to indicate that both ultrasonic velocity measurements and resonant inspection testing offer unique capabilities in the evaluation of PM components. The rapid, full-body inspection offered by RI testing is attractive from a manufacturing perspective, once the correlation between acceptable part performance and resonant response spectra is made. The measurement of ultrasonic velocity can provide much insight into the effect of component design in complex PM parts, particularly with respect to how geometry affects density distributions. Some part geometries, however, might require unusual testing constraints or even rudimentary machining, as was done in this project, to facilitate getting useful information. Both techniques were utilized in this work to provide different and complimentary information regarding a true inspection challenge in the manufacturing world.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the funding supplied by Square D to lease the resonant inspection equipment from Magnaflux for this work. The Iowa Demonstration Laboratory functions under funds administered by the Institute for Physical Research and Technology at Iowa State University.

REFERENCES

1. D. Utrata and J. Oswood, "Practical applications of Resonant Inspection for Evaluation of Electrical Components," MPIF seminar: *Applications of Nondestructive Evaluation Powder Metallurgy*, Ames, IA, July 7-8, 1998.
1. A. Dawson, J. Bussière, S. Pelletier, L. Piche, M. Dubois, L. Lefebvre, and A. Hammel, "Ultrasonic Evaluation of P/M Parts During Production," *ibid.*
2. D. Foley, "CAT – Computer Aided Testing for Resonant Inspection," *ibid.*
3. R. M. German, *Powder Metallurgy Science*, 2nd edition, Metal Powder Industries Federation, Princeton, New Jersey, 1997.